

# Possible studies of explosively driven non-ideal plasma using a proton microscope at the Facility for Antiprotons and Ion Research

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**Abstract.** The article describes possible experiments with explosively driven non-ideal plasma at the proton microscope at the Facility for Antiprotons and Ion Research. It is proposed to employ linear explosive tubes for plasma generation and to measure an areal density in shock-compressed plasma of argon and xenon. The proposed experiments will provide valuable information on influence of strong interparticle interactions on thermodynamic properties of strongly coupled plasma. The density measurement will help the researchers to understand the nature of wall and wire precursors arising in the shock tubes.

## 1. Introduction

Methods and techniques of non-destructive testing and non-invasive analysis have been developed for a long time. Continuous interest in them is determined by numerous medical, technical and scientific applications. The first proton radiographs of dense objects [1, 2] showed high contrast images in comparison with conventional x-ray images. It was also specified that multiple Coulomb scattering of protons in the studied object seriously blurs the radiographic image and limits the image resolution. This issue was partially fixed by special magnetic lens system [3] developed for focusing the low-angle scattered protons exiting each point of the object onto a distant image plane. The modern radiography systems with magnetic optics provide high spatial resolution at the level of 17–180  $\mu\text{m}$  depending on the thickness of the studied object [4, 5]. Typical time resolution of proton radiography is several tens of nanoseconds and it is defined by the parameters of image registration system, the intensity and temporal structure of the proton beam. Such high parameters became available after an electronic multi-frame camera system with intensification and electro-optic shutter was designed for investigation of fast dynamical



processes. It was tested in experiments with high explosives at the Los Alamos Neutron Science Center (LANSCE) using 800 MeV protons [6]. This approach was reproduced at other facilities later. A non-uniform spatial distribution of protons, a variability of beam from pulse to pulse and pattern noise from the charge-coupled device cameras are other serious issues related to density reconstruction from proton radiographs. The possible solutions were presented in [7]. One of alternative methods includes correction of both the object and the beam images and normalization (i.e., division) radiographs using images of the raw beam. A review of proton radiography systems constructed for investigation of fast dynamic processes before 2013 can be found in [8].

A high energy proton microscope for the Facility for Anti-proton and Ion Research (PRIOR) was put into operation at the GSI in Germany [9] later. It is expected that the areal density in dynamical experiments could be measured at the PRIOR with sub-percent accuracy. It could strongly improve the accuracy of density determination in many challenging physical tasks conducted at the GSI and related to high dynamic pressures. At present only two proton radiography facilities LANSCE in the USA [10] and at the Institute for High Energy Physics in Russia [11] are equipped with special steel chambers, where high explosives are used for generation of states of matter at high pressures, temperatures and energy densities. The explosive chamber for charges with mass up to 200 g of high explosive has already been used for investigations of stopping power of ions in explosively driven non-ideal plasmas [12] at the GSI. The technical details on matching the same explosive chamber and the linear proton accelerator at the Institute for Theoretical and Experimental Physics (ITEP) is published in [13]. This chamber could be employed with proton microscope and then the PRIOR will be the third proton radiography system in the world suitable for investigation of explosively driven phenomena. The application of explosive generators of high pressures at the PRIOR will give wide opportunities to conduct research in the following branches: non-ideal plasmas, warm dense matter, phase transitions in condensed matter, chemical physics, shock wave synthesis of high pressure phases, extreme states of matter, physics of detonation and others.

The purpose of this article is a justification of application of the proton microscope PRIOR at the Facility for Anti-proton and Ion Research (FAIR) for investigation of equation of state of shock-compressed non-ideal plasma and related phenomena like wall and probe precursors arising in shock tubes. In this article, we propose two different types of proton radiography experiments for precise measurements of density of shock-compressed plasma which cannot be done by other experimental techniques. The aim of the first type of experiments is the density measurements of shock-compressed plasma of heavy inert gases. Such approach has not been earlier applied for systematic investigations of equation of state of strongly coupled plasma. It has large potential as it allows simultaneous measurements of density and kinematic parameters of a gas-dynamic flow. Details of the proposed experiments and a possible design of explosive generator of non-ideal plasma suitable for beam experiments are described in section 2.

The second type of proposed experiments will focus on measurements of distribution of density of wall and wire precursors arising in shock tubes. The goal of this type of experiments is determination of the nature of wire and wall precursors in shock tubes. In section 3 we present the experimental streak images of light emitted from the front of shock-compressed plasma produced in the developed linear generator. Gas-dynamic flows with or without a wall precursor were obtained by varying the gas type, the initial gas pressure, the shock wave front velocity.

## 2. Density of shock-compressed non-ideal plasma of inert gases

The goal of this type of experiments will be the density measurement of a non-ideal plasma ( $\Gamma = E_{\text{INT}}/E_{\text{KIN}} > 1$  is a parameter of Coulomb non-ideality,  $E_{\text{INT}}$  is the energy of Coulomb inparticle interaction,  $E_{\text{KIN}}$  is the thermal energy of particles). A non-ideal plasma is still a complex object for strict theoretical approaches due to the difficulties of correct accounting of

strong interparticle interactions [14]. The direct experimental information on the density is very important for understanding the influence of Coulomb interaction on thermodynamic properties of strongly coupled plasma. The proposed experiment provides important data for development of equation of state of non-ideal plasma also. Shock wave is an excellent experimental technique of compression and irreversible heating of matter, which takes place behind the front of a shock wave. Shock waves in gases are often driven by energy of high explosives in shock tubes [15]. Thermodynamic, transport and optic properties of strongly coupled plasma [16] are investigated in explosive generators. They allow generation of plasma slugs with typical size of several centimeters. The density of shock-compressed non-ideal gaseous plasma was earlier defined by x-ray pulse radiography [17] or derived from the conservation laws by the measured kinematic parameters of the gas-dynamic flow [18]. The conservation law of mass on a shock wave discontinuity in initially motionless medium and strong shock wave may be represented in the form as

$$\frac{\rho}{\rho_0} = \frac{D}{D - U}, \quad (1)$$

where  $D$  is the velocity of the shock wave front,  $U$  is the velocity of shock-compressed plasma,  $\rho_0$  is the density of uncompressed gas,  $\rho/\rho_0$  is the ratio of gas compression. Velocities  $D$  and  $U$  have close values in inert gases in case of intense shock waves, which leads to a big error of the denominator. The typical accuracy of density determination by the measured  $D$ ,  $U$  and  $\rho_0$  was about 10%. The estimates of experimental errors are presented in [19]. It is expected that the accuracy of areal density measurements in a dynamic experiment at the PRIOR will be better. It could be improved for low density objects by applying an inverse collimator, which was developed for proton radiography of thin objects. The corresponding results on the density measurements of weakly non-ideal xenon plasma are presented in [20].

Non-ideal plasma could be obtained behind explosively driven shock waves in heavy inert gases. Optimum parameters of an explosive experiment with xenon and argon gases are specified in the work [21]. Xenon is more preferable since allows to obtain greater values of parameter of non-ideality. The value of velocity of a shock wave front in xenon should be about 5 km/s to generate non-ideal plasma in the gas at initial pressure more than 1 bar. The thickness of singly compressed plasma slug is roughly proportional to the distance passed by a shock wave in uncompressed gas. The increase of the thickness  $\Delta h$  is proportional to a difference of the front speed  $D(t)$  and the velocity  $U(t)$  of shock-compressed plasma:

$$\Delta h = (D(t) - U(t))\Delta t. \quad (2)$$

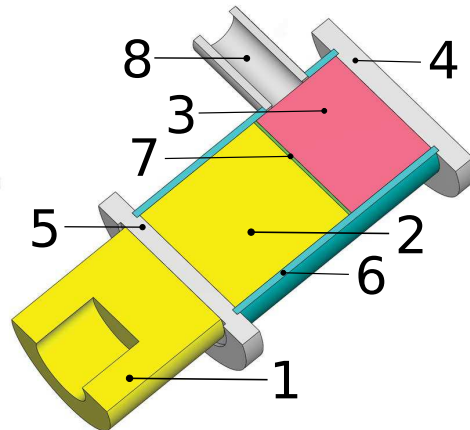
A variation of plasma parameters is reached by the change of speed of the shock wave front and the change of initial pressure of gas. The pressure  $P$  and the specific internal energy  $E$  of a shock compressed plasma could be derived from the conservation laws of momentum and energy:

$$P = P_0 + \rho_0 D U, \quad (3)$$

$$E - E_0 = \frac{1}{2}(P + P_0) \left( \frac{1}{\rho_0} - \frac{1}{\rho} \right), \quad (4)$$

where  $P_0$  and  $E_0$  are the values of pressure and specific internal energy of uncompressed gas. The plasma temperature could be estimated only using the particular equation of state.

A compact linear explosive generator of shock-compressed plasma of xenon or argon [22] was developed for experiments at the proton radiographic system with magnetic optics (PUMA) at the ITEP [23, 24] earlier. Single shock-compressed plasma of xenon or argon with pressures of several kbars, temperatures of 2–3 eV and Coulomb parameter of non-ideality up to 2 was investigated at the PUMA, the typical proton radiographs were published in [25]. The results of simulation of proton radiography experiments with static model of shock-compressed xenon



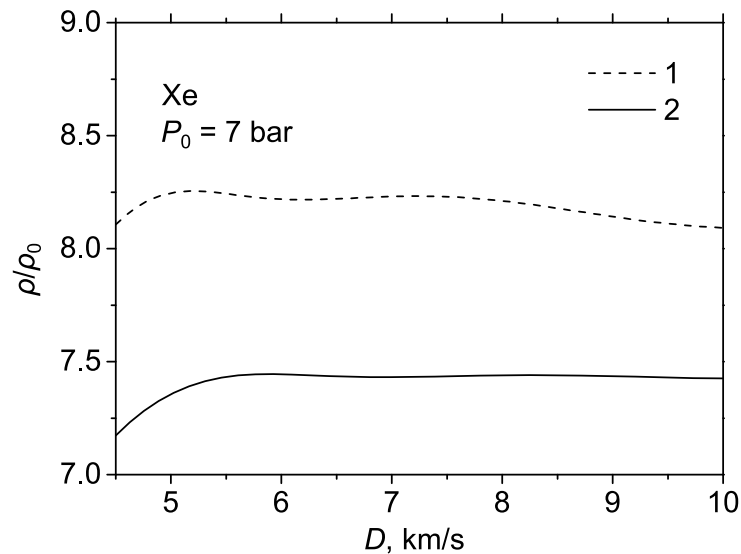
**Figure 1.** A cross view of a linear explosive generator of non-ideal plasma: 1—charge with hollow for a detonator; 2—active charge; 3—inert gas; 4—top flange; 5—flange for charges mounting; 6—channel; 7—copper foil; 8—gas inlet.

are presented in [26]. The current design of the PRIOR microscope provides a magnification of about four with a 15 mm field of view. Both parameters will be increased by a factor of 2–3 at the FAIR. The external diameter of the generator of 25 mm is less than the future field of view of the PRIOR microscope of 40 mm. It contains an explosive charge of 20 g and could be easily adapted to experimental conditions at the FAIR. A cross-view of this generator with gas inlet on the surface of the channel is shown in figure 1.

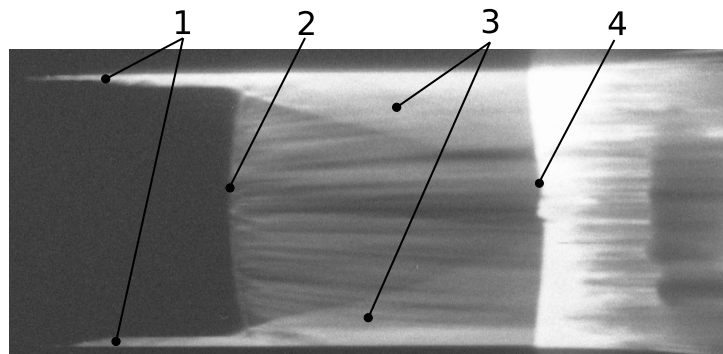
This design has slight differences from the classic design. A thin copper foil at the top of the active charge is used as a contrast marker to determine the velocity of detonation products equal to the velocity of shock-compressed plasma. The channel effect [27] was organized in a gas gap between the active charge and the generator wall to flatten the detonation front. An explosive lens also could be applied for this purpose. The generator channel is manufactured of polyvinylchloride or organic glass tube with thickness of 1–2 mm, which depends on the initial gas pressure in the channel. The generator with flanges glued to the generator channel keeps air-tightness up to the pressure of 2–3 bar. The generator design with flanges pressed in ring grooves made on the inner surface of the channel was applied at the pressures up to 12 bar.

Some experimental results on thermodynamic properties of non-ideal xenon plasma obtained in this generator are published in [28]. Plasma states with the pressure of 5–12 kbar, the density of 0.24–0.3 g/cm<sup>3</sup> were investigated by a high-speed photography at the initial pressure of xenon of 7 bar. Figure 2 shows difference between the Hugoniot curves of xenon at the initial pressure of 7 bar calculated from different modifications of chemical model [29] of plasma. The calculation was carried out according to the procedure described in [30].

Coulomb interactions are considered in frames of the Debye approximation in a grand canonical ensemble [31] or as gas of non-interacting particles. Only ground states were taken into account when calculating partition functions. The compression ratios for these basic models differ about 10% and this difference of density is highly desirable to be resolved at the PRIOR. The resulting areal density of walls of the generator with shock-compressed xenon at initial pressure 7 bar is about of 0.8 g/cm<sup>2</sup> in the widest section. The jump of the areal density in xenon to be measured at the PRIOR is about of 0.5–0.6 g/cm<sup>2</sup> in this experiment. A high speed filming of processes in the generator can be realized, if the top flange or the channel is manufactured of transparent materials.



**Figure 2.** Calculated Hugoniot curves of xenon at initial pressure of 7 bar and initial density of  $3.95 \times 10^{-2}$  g/cm<sup>3</sup>: 1—Debye approximation in a grand canonical ensemble; 2—ideal gas approximation.

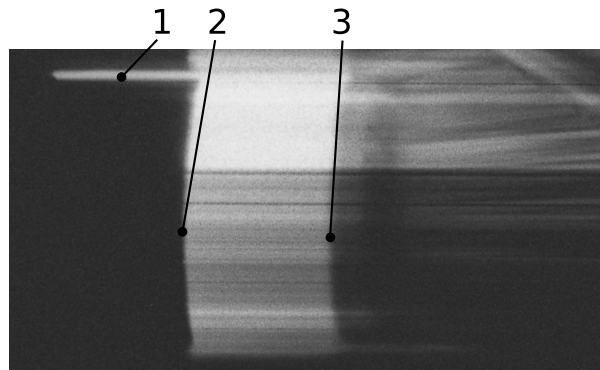


**Figure 3.** Streak photography of a flow with the wall precursor in argon at normal initial conditions: 1—channel effect; 2—exit of a detonation wave on free surface of a charge; 3—shock wave precursor; 4—beginning of reflection of shock wave from top flange.

### 3. Wall and wire precursors in shock tubes

Instability of a flat front sometimes arises, when a strong shock wave propagates along a channel filled by some heavy inert gas like argon or xenon. It was first time noted in [32] that high-speed boundary disturbance propagates along the walls of an explosive shock tube in advance of the plane shock. The wall precursor can slow down over time and then the front of the shock wave restores the flat form, then it can arise again. Physics of these processes is understudied yet. There are several possible explanations like heating of the wall by light emitted by a shock wave, friction about a wall, reflection of an oblique shock wave. Density measurements are needed to understand the nature of the wall precursor.

Various modifications of the described shock tube can be used to generate shock waves to study this physical effect. Relevant streak images of light emitted from the top transparent flange are shown in figures 3 and 4. Time increases in the horizontal direction from left to right, space along the tube section is shown in the vertical azimuth. The shock wave precursor in



**Figure 4.** Streak photography of a flow without the wall precursor in xenon at initial pressure 9.2 bar: 1—channel effect; 2—exit of a detonation wave on free surface of a charge; 3—beginning of reflection of shock wave from top flange.

argon at normal initial conditions is presented in figure 3. The streak image of a gas-dynamic flow in xenon at initial pressure 9.2 bar without the wall precursor is shown in figure 4. The camera slit had a slightly V-shaped form to increase the dynamic range of the image; therefore the upper part of figure 4 is brighter than the lower one.

The shock precursor can be formed on a wire, which is placed perpendicular to the shock wave front [32, 33]. Pairs of wires are used in probe techniques of determination of static electrical conductivity [34] and electronic concentration [35] of shock-compressed gas plasma. The presence of wire or wall precursors could disturb the plasma homogeneity resulting in distortions of probe measurements of galvanomagnetic properties of plasma. For this reason proton radiographic investigations of plasma density around a wire precursor or interacting two wire precursors are of great interest to plasma probe diagnostics.

#### 4. Conclusions

Two experimental proposals for explosively driven shock-compressed plasma research using the proton microscope PRIOR at the FAIR are justified. The plasma will be generated in explosive shock tubes optimized for proton radiography. An influence of strong interparticle interactions on thermodynamic properties of strongly coupled plasma and its equation of state will be explored in the first type of the suggested experiments. Other interesting unsolved problems of shock wave physics are mechanisms of generation of wall and wire precursors in shock tubes filled by heavy inert gases, which will be investigated in the second type of experiments at the PRIOR microscope.

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